

Characterizing quark gluon plasma by dilepton interferometry

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Abstract

The Hanbury-Brown-Twiss (HBT) radii have been calculated from the two particle correlation functions with virtual photons produced in the collisions of two nuclei at ultra-relativistic energies. We show that the variation of the HBT radii with the invariant mass of the virtual photon can be used to characterize and distinguish the hadronic as well as the partonic phase that might have produced initially in the collisions. It has been illustrated that the non-monotonic variation of the HBT radii with invariant mass provides an access to the development of collective flow in the system.

Key words: Heavy ion collision, quark gluon plasma, photons, dileptons.

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The aim of the nuclear collisions at ultra-relativistic energies is to create and study - a state of matter, where quarks and gluons are dislocated from individual hadrons and make an excursion over a nuclear volume - such a phase of matter is called quark gluon plasma (QGP). Several probes - both electromagnetic (EM) and hadronic have been proposed for the diagnostics of QGP. The electromagnetically interacting probes (real and virtual photons) has the advantage over the hadronic probes because of their nature of interaction. The EM probes has mean free path much larger than the size of the system as a consequence they leave the system without re-scattering and hence can transmit the source information very efficiently [1]. However, photons and lepton pairs can be produced from both the partonic as well as hadronic phases [2]. As a consequence the disentanglement of the contribution for the QGP still remains a big challenge.

In case of EM probes- dilepton has the advantage over the real photons. The photons with low transverse momentum (k_T) from the hadronic phase may receive large transverse kick due to radial flow and consequently appear as high k_T photons. These photons can mingle with the the contributions from the high temperature QGP

phase, making the detection of photons from QGP difficult. However, for dileptons there are two kinematic variables available - the k_T and the invariant mass (M). While the k_T spectra of dilepton is affected by the flow, the k_T integrated M spectra remains unchanged. This suggests that a careful selection of k_T and M windows will be very useful to characterize the QGP and the hadronic phases.

The interferometry of the dilepton pairs actually reflect correlation between two virtual photons, the analysis then concentrates on computing the Bose-Einstein correlation (BEC) function for two virtual photons which can be defined as,

$$C_2(\vec{k}_1, \vec{k}_2) = 1 + \frac{[\int d^4x \omega(x, K) \cos(\Delta\alpha)]^2 + [\int d^4x \omega(x, K) \sin(\Delta\alpha)]^2}{P_1(\vec{k}_1)P_1(\vec{k}_2)} \quad (1)$$

where k_i is momentum of the individual photon, $K = (k_1 + k_2)/2$, $\Delta\alpha = \alpha_1 - \alpha_2$, $\alpha_i = \tau M_{iT} \cosh(y_i - \eta) - rk_{iT} \cos(\theta - \psi_i)$, $M_{iT} = \sqrt{k_{iT}^2 + M^2}$ is the transverse mass and $\omega(x, K)$ is the source function related to the thermal emission rate of the virtual photons per unit four volume (see [3,4] for details).

For the space time evolution of the system relativistic hydrodynamical model with cylindrical symmetry [5] and boost invariance along the longitudinal direction [6] has been used. For a system undergoing isentropic expansion, the initial temperature (T_i) and proper thermalization time (τ_i) of the system may be constrained by the measured hadronic multiplicity, $dN/dy \sim T_i^3 \tau_i$. Here we have taken $T_i = 290$ MeV and $\tau_i = 0.6$ fm/c. The equation of state (EoS) which controls the rate of expansion/cooling has been taken from the lattice QCD calculations [7]. The chemical ($T_{ch}=170$ MeV) and kinetic ($T_{fo}=120$ MeV) freeze-out temperatures are fixed by the particle ratios and the slope of the k_T spectra of hadrons [8]. With all these ingredients the correlation function C_2 has been evaluated for different invariant mass windows ($\langle M \rangle = (M_1 + M_2)/2 = 0.3, 0.5, 0.7, 1.2, 1.6$ and 2.5 GeV) as a function of q_{side} and q_{out} [3] which are related to transverse momentum of individual pair. Once the correlation function for the (time like) virtual photon is calculated, the source dimensions can be obtained by parameterizing it with the empirical (Gaussian) form:

$$C_2 = 1 + \frac{\lambda}{3} \exp(-R_i^2 q_i^2). \quad (2)$$

where the subscript i stand for *out* and *side*. In Eq. 2 λ represents the degree of chaoticity of the source. Deviation of λ from 1 will indicate the presence of non-chaotic sources.

The R_{side} , radius corresponding to q_{side} is closely related to the transverse size of the system and considerably affected by the collectivity and the R_{out} , radius corresponding to q_{out} measures both the transverse size and duration of particle emission [9,10]. The R_{side} shows non-monotonic dependence on $\langle M \rangle$ (Fig. 1a). It can be shown that $R_{side} \sim 1/(1 + E_{collective}/E_{thermal})$. With the transverse expansion the radial size

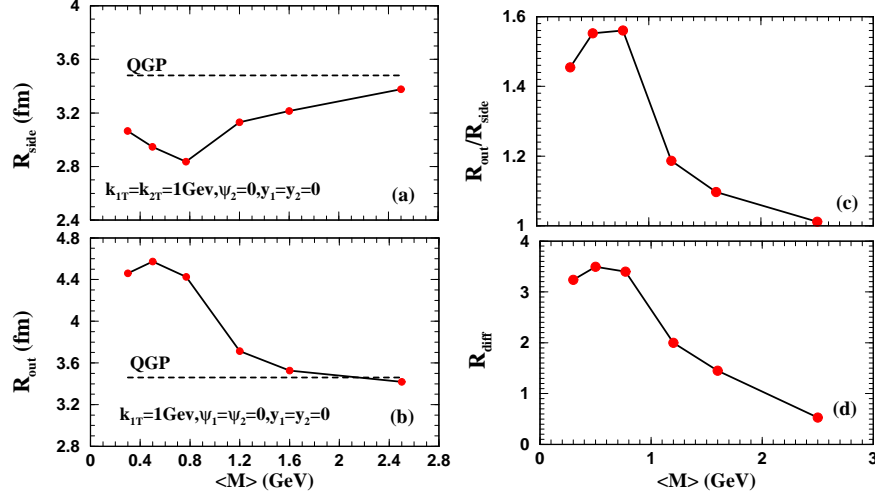


Fig. 1. The variation of R_{side} and R_{out} as a function of $\langle M \rangle$ (left panel). The right panel show R_{out}/R_{side} and $R_{diff} = \sqrt{R_{out}^2 - R_{side}^2}$ as a function of $\langle M \rangle$.

of the emission zone decreases with time as a rarefaction wave moves toward the center of the cylindrical geometry. The high $\langle M \rangle$ regions are dominated by the early partonic phase [3] where the collective flow has not been developed fully [11] consequently the ratio of collective to thermal energy is small- hence a larger R_{side} is obtained for large M . In contrast, the lepton pairs with $M \sim m_\rho$ are emitted from the late hadronic phase where the size of the emission zone is smaller due to larger collective flow giving rise to a smaller R_{side} . The ratio of collective to thermal energy for such cases is quite large, which is reflected as a dip in the variation of R_{side} with $\langle M \rangle$ around the ρ -mass region (Fig. 1a). Thus the variation of R_{side} with M can be used as an efficient tool to measure the collectivity in various phases of matter. The dip, in fact vanishes if the contributions from ρ and ω is switched off [4]. We observe that by keeping the ρ and ω contributions and setting radial velocity, $v_r = 0$, the dip in R_{side} vanishes, confirming the fact that the dip is caused by the large radial flow of the hadronic matter [4]. The R_{out} probes both the transverse dimension as well as the duration of emission and unlike R_{side} , R_{out} does not remain constant even in the absence of radial flow. The large M regions are populated by lepton pairs from early partonic phase where the effect of flow is small and the duration of emission is also small - resulting in smaller values of R_{out} . For lepton pair from $M \sim m_\rho$ region the flow is large which could have resulted in a dip as in R_{side} in this M region. However, R_{out} probes the duration of emission too which is large for hadronic phase. The larger duration overwhelms the reduction of R_{out} due to flow in the hadronic phase resulting in a bump in R_{out} in this region of M (Fig. 1b).

Figs. 1(c) and 1(d) show the variation of R_{out}/R_{side} and $R_{diff} = \sqrt{R_{out}^2 - R_{side}^2}$ with $\langle M \rangle$. These two quantities provides information on the duration of particle emission [10] for various domains of M . In one hand the high and low M domains are dominated by radiation from early QGP phase [4] where the duration of particle emission is small. On the other hand the lepton pairs for M around ρ mass dominantly

originate from the late hadronic phase where the duration of particle emission is large, Resulting in a non-monotonic variation of R_{diff} , which indicates the presence two different phases during the evolution.

In summary, we have evaluated the dilepton pair correlation functions relevant for Au+Au collisions at RHIC energy. The values of HBT radii extracted from the dilepton correlation functions show non-monotonic dependence on dilepton pair mass, reflecting the evolution of collective flow in the system. It appears that the non-monotonic variation of R_{out} and R_{side} with M originate from the presence of two phases during the evolution of the system, hence could be use as a signal of phase transition.

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